Production of $J/\psi$ and $\Upsilon$ mesons in proton-lead collisions at $\sqrt{s_{NN}} = 5$ TeV

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on behalf of the LHCb collaboration

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Outline

- The LHCb detector and $p$Pb data taking
- Physics motivation
- $J/\psi$ production and nuclear effects in $p$Pb at 5 TeV
  [ JHEP 02 (2013) 072 ]
- $\Upsilon(nS)$ production and nuclear effects in $p$Pb at 5 TeV
  [ arXiv:1405.5152 ]
- Summary and prospects
LHCb detector

Dedicated to beauty and charm physics

Pseudorapidity acceptance $2 < \eta < 5$

beam 2

beam 1

can also contribute to heavy-ion physics ...
LHCb in a nutshell

Impact parameter: \( \sigma_{IP} = 20 \, \mu m \)
Proper time: \( \sigma_\tau = 45 \, \text{fs} \) for \( B_s^0 \rightarrow J/\psi \phi \) or \( D_s^+ \pi^- \)
Momentum: \( \Delta p/p = 0.4 \sim 0.6\% \) (5 – 100 GeV/c)
Mass: \( \sigma_m = 8 \, \text{MeV}/c^2 \) for \( B \rightarrow J/\psi X \) (constrained \( m_{J/\psi} \))
RICH \( K \rightarrow \pi \) separation: \( \epsilon(K \rightarrow K) \sim 95\% \) mis-ID \( \epsilon(\pi \rightarrow K) \sim 5\% \)
Muon ID: \( \epsilon(\mu \rightarrow \mu) \sim 97\% \) mis-ID \( \epsilon(\pi \rightarrow \mu) \sim 1 \sim 3\% \)
ECAL: \( \Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})} \)

\( \gamma(1S) \) JHEP 06 (2013) 064
\( \gamma(2S) \)
\( \gamma(3S) \)
Beam configuration

- Asymmetric beam energy
  - $E_p = 4$ TeV
  - $E_N = 1.58$ TeV for lead beam
  - $\sqrt{S_{NN}} = 5$ TeV
  - Rapidity shift $\Delta y = \pm 0.465$

- Rapidity coverage (in NN c.m.s. frame)
  - Forward direction ($pPb$)
    - $1.5 < y < 4.0$
  - Backward direction ($Pbp$)
    - $-5.0 < y < -2.5$

- Common coverage
  - $2.5 < |y| < 4.0$
2013 $p$Pb data taking

- $\sqrt{s_{NN}} = 5$ TeV
- Low instantaneous luminosity ($\sim 5 \times 10^{27}$ cm$^{-2}$s$^{-1}$)
- Low pile-up
- Four configurations: $p$Pb (Pbp), Magnet Up(Down)

Integrated luminosity after data quality:
Forward ($p$Pb) : 1.1 nb$^{-1}$
Backward (Pbp): 0.5 nb$^{-1}$
Event display and track multiplicity

- Magnetic Up/Down agree for both $p$Pb and Pb$p$
- Higher multiplicities in Pb$p$ as expected
Physics motivation

- pA collisions are important to study **cold nuclear matter effects**
- Cold nuclear matter effects are of great interest by themselves, in addition to QGP studies
- Insight to unexplored region of QCD phenomena
- Constrain nuclear Parton Density Function at low $x$ over wide $Q^2$
- LHCb can play an important role
- Unique rapidity coverage with **full particle identification**

Heavy quarkonia suppression in pA

- Important probes of QGP, and also
- Sensitive to cold nuclear matter effects
  - Strongly suppressed in pA collisions at large rapidity
- Cold nuclear matter effects characterized by

**Nuclear modification factor:**

$$R_{pA}(y, \sqrt{S_{NN}}) = \frac{1}{A} \cdot \frac{\frac{d\sigma_{pA}}{dy}(y, \sqrt{S_{NN}})}{\frac{d\sigma_{pp}}{dy}(y, \sqrt{S_{NN}})}$$

**Forward-backward production ratio:**

$$R_{FB}(y, \sqrt{S_{NN}}) = \frac{\sigma_{pA}(+|y|, \sqrt{S_{NN}})}{\sigma_{pA}(-|y|, \sqrt{S_{NN}})}$$
$J/\psi$ production and cold nuclear matter effects in $p\text{Pb}$ collisions at $\sqrt{s_{NN}} = 5$ TeV

[ JHEP 02 (2014) 072 ]
Analysis strategy

- Reconstructed using $J/\psi \rightarrow \mu^+ \mu^-$ decay channel

- Measurement performed in bins of $p_T$ and $y$

$$\frac{d^2\sigma}{dp_Tdy} = \frac{N_{\text{corr}}(J/\psi \rightarrow \mu^+ \mu^-)}{\mathcal{L} \times \text{Br}(J/\psi \rightarrow \mu^+ \mu^-) \times \Delta p_T \times \Delta y}$$

- Three sources of $J/\psi$ at hadron colliders
  - Direct $J/\psi$
  - Feed-down from heavier $c\bar{c}$ states
  - From $b$-hadron decays

- Prompt $J/\psi$ and $J/\psi$ from $b$ separated by pseudo proper time $t_z = d_z \times \frac{M_{J/\psi}}{p_{J/\psi}}$.

Note:
Cold nuclear matter effects on $J/\psi$ from $b$ reflect those on $b$ hadrons!
**$J/\psi$ signal extraction**

- Yields of prompt $J/\psi$ and $J/\psi$ from $b$ extracted in each ($p_T, y$) bin from simultaneous fit to mass and pseudo proper time $t_z$

**Mass distribution**
- Signal by Crystal Ball function
- Background by exponential

**$t_z$ distribution**
- Prompt signal
  - $\delta$-function $\otimes f_{res}$
- Non-prompt signal
  - Exponential $\otimes f_{res}$
- Background
  - Empirical functions from sidebands

<table>
<thead>
<tr>
<th>Signal yield</th>
<th>Forward</th>
<th>Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt $J/\psi$</td>
<td>25,280 ± 240</td>
<td>8,830 ± 160</td>
</tr>
<tr>
<td>$J/\psi$ from $b$</td>
<td>3,720 ± 80</td>
<td>890 ± 40</td>
</tr>
</tbody>
</table>
Total $J/\psi$ cross-sections in $pPb$

\[ \sigma_F(\text{prompt } J/\psi, +1.5 < y < +4.0) = 1,168 \pm 15 \pm 54 \text{ } \mu b \]

\[ \sigma_B(\text{prompt } J/\psi, -5.0 < y < -2.5) = 1,293 \pm 42 \pm 75 \text{ } \mu b \]

\[ \sigma_F(J/\psi \text{ from } b, +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2 \text{ } \mu b \]

\[ \sigma_B(J/\psi \text{ from } b, -5.0 < y < -2.5) = 118.2 \pm 6.8 \pm 11.7 \text{ } \mu b \]

\[ (p_T < 14 \text{ GeV}/c) \]

Systematics dominated by:

- mass fit model
- luminosity
- data-MC disagreement

<table>
<thead>
<tr>
<th>Source</th>
<th>Forward (%)</th>
<th>Backward (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlated between bins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass fits</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Radiative tail</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Muon identification</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

| Uncorrelated between bins     |             |              |
| Binning                       | 0.1 – 8.7   | 0.1 – 6.1    |
| Multiplicity weight           | 0.1 – 3.0   | 0.2 – 4.3    |
| $t_z$ fit (only for $J/\psi$ from $b$) | 0.2 – 12   | 0.2 – 13    |
Single differential $J/\psi$ cross-sections

JHEP 02 (2014) 072

Forward ($pPb$)

Backward ($Pbp$)

Forward ($pPb$)

Backward ($Pbp$)
Double differential $J/\psi$ cross-sections

- Statistics in forward sample ($p$Pb) allow measurements of double differential cross-section

![Graphs showing double differential cross-sections for prompt $J/\psi$ and $J/\psi$ from $b$]
Reference cross-sections in $pp$ at $\sqrt{s} = 5$ TeV

- Input to the determination of the nuclear modification factor $R_{ppb}$
- Interpolated from measurements at 2.76 TeV, 7 TeV and 8 TeV
- Three different fit functions used to interpolate
  $$\frac{(\sqrt{s}/p_0)^{p_1}}{p_0 + p_1\sqrt{s}} \quad \frac{p_0(1 - e^{p_1\sqrt{s}})}{p_0}$$  
  adopted as nominal
- Discrepancy between the three interpolated values taken as systematics
- Checked against functions from LO-CEM and FONLL
Nuclear modification factor $R_{pPb}$ for $J/\psi$

- Strong dependence on rapidity
- $J/\psi$ form $b$ less suppressed in forward than prompt $J/\psi$
  $\Rightarrow b$ hadrons less affected by cold nuclear matter effects
- Agreement with theoretical predictions
- Precision insufficient to distinguish different models

![Graph showing $R_{pPb}$ for $J/\psi$](image)

**References**
- JHEP 03 (2013) 122
- JHEP 03 (2013) 122
- arXiv:1402.1747
Forward-backward production ratio $R_{FB}$

- Independent of $pp$ cross-sections
- Part of experimental and theoretical uncertainties cancel
- Clear difference between prompt $J/\psi$ and $J/\psi$ from $b$

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prompt $J/\psi$

$J/\psi$ from $b$

$R_{FB}$

$J/\psi$ from $b$

EPS09 LO

E. loss

nDSg LO

Int. J. Mod. Phys. E22 (2013) 1330007


JHEP 03 (2013) 122

arXiv:1402.1747
Comparison with ALICE

Measurements agree with each other

LHCb-CONF-2013-013
γ production and cold nuclear matter effects in \( pPb \) collisions at \( \sqrt{s_{NN}} = 5 \) TeV

[ arXiv:1405.5152 ]
$\Upsilon(nS)$ signal extraction

- Reconstructed using $\Upsilon(nS) \rightarrow \mu^+ \mu^-$ decay channel
- Signal modelled by three Crystal Ball functions
- Background modelled by exponential

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<th>Signal yield</th>
<th>Forward $(pPb)$</th>
<th>Backward $(Pbp)$</th>
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<tr>
<td>$\Upsilon(1S)$</td>
<td>$189 \pm 16$</td>
<td>$72 \pm 14$</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>$41 \pm 9$</td>
<td>$17 \pm 10$</td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>$13 \pm 7$</td>
<td>$4 \pm 8$</td>
</tr>
</tbody>
</table>

arXiv:1405.5152
$\Upsilon(nS)$ cross-section in $p\text{Pb}$

- Total cross-section with $p_T < 15$ GeV/$c$ measured
- Systematic uncertainty dominated by mass fit model, data-MC discrepancy, and trigger efficiency

\[
\begin{align*}
\sigma(\Upsilon(1S), -5.0 < y < -2.5) \times B(1S) &= 295 \pm 56 \pm 29 \text{ nb} \\
\sigma(\Upsilon(2S), -5.0 < y < -2.5) \times B(2S) &= 81 \pm 39 \pm 18 \text{ nb} \\
\sigma(\Upsilon(3S), -5.0 < y < -2.5) \times B(3S) &= 5 \pm 26 \pm 5 \text{ nb} \\
\sigma(\Upsilon(1S), 1.5 < y < 4.0) \times B(1S) &= 380 \pm 35 \pm 21 \text{ nb} \\
\sigma(\Upsilon(2S), 1.5 < y < 4.0) \times B(2S) &= 75 \pm 19 \pm 5 \text{ nb} \\
\sigma(\Upsilon(3S), 1.5 < y < 4.0) \times B(3S) &= 27 \pm 16 \pm 4 \text{ nb}
\end{align*}
\]

- Production ratios $R^{nS/1S} \equiv \frac{\sigma(\Upsilon(nS)) \times Br(\Upsilon(nS) \rightarrow \mu^+ \mu^-)}{\sigma(\Upsilon(1S)) \times Br(\Upsilon(1S) \rightarrow \mu^+ \mu^-)}$ measured $(n = 2, 3)$

\[
\begin{align*}
R^{2S/1S}(-5.0 < y < -2.5) &= 0.28 \pm 0.14 \pm 0.05 \\
R^{3S/1S}(-5.0 < y < -2.5) &= 0.02 \pm 0.09 \pm 0.02 \\
R^{2S/1S}(1.5 < y < 4.0) &= 0.20 \pm 0.05 \pm 0.01 \\
R^{3S/1S}(1.5 < y < 4.0) &= 0.07 \pm 0.04 \pm 0.01
\end{align*}
\]

consistent with $pp$ results but limited by statistics

$R^{2S/1S}(pp) \sim 0.24$

$R^{3S/1S}(pp) \sim 0.12$
Nuclear modification factor for $\Upsilon(1S)$

- Reference $pp$ cross-section interpolated as done for $J/\psi$
- Forward region: suppression smaller than prompt $J/\psi$, and compatible with $b$ hadrons
- Backward region: indication of antishadowing effect
- Consistent with different theoretical models with large uncertainty

Theoretical predictions:
EPS09 LO: EPJC 73 (2011) 2427
EPS09 NLO: IJMP E22 (2013) 1330007
E. loss: JHEP 03 (2013) 122
Forward-backward production ratio $R_{FB}$

- Independent of $pp$ cross-sections
- Part of experimental and theoretical uncertainties cancel
- Agreement with different theoretical models, but statistical uncertainty large

Theoretical predictions:
- EPS09 LO: EPJC 73 (2011) 2427
- EPS09 NLO: IJMP E22 (2013) 1330007
- E. loss: JHEP 03 (2013) 122
Summary and prospects

- Study of pA collisions is important for probing some unexplored QCD physics, and provides inputs for QGP studies.
- LHCb has recorded about $1.8 \text{ nb}^{-1}$ pPb data in a unique kinematic range with full particle identification.
- Production cross-sections measured for prompt $J/\psi$, $J/\psi$ from $b$, and $\Upsilon(nS)$.
- Nuclear modification factor $R_{pPb}$ and forward-backward production ratio $R_{FB}$ determined for prompt $J/\psi$, $J/\psi$ from $b$, and $\Upsilon(1S)$.
- Measurements agree with theoretical models, but power to distinguish different models is limited by statistics.
- Further analyses under way, $\psi(2S)$, ridge effect, etc.
- Looking forward to 10-times more integrated luminosity in Run II.

Thank you!
Backup slides
Efficiency for $J/\psi$

Efficiencies $\epsilon_{tot} = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{trig}$ ($\sim 45\%$)

- $\epsilon_{acc}$: geometric acceptance
  - estimated from simulation with unpolarized $J/\psi$
- $\epsilon_{rec}$: including reconstruction and selection
  - estimated from simulation
- $\epsilon_{trig}$: trigger efficiency
  - obtained from the minimum-bias sample collected in the data